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Analytical Calculations of Helicopter Torque Coefficient (C_Q) and Thrust Coefficient (C_T) Values for the **He**licopter **P**erformance (HELPE) Model

Ki C. Kim

ARL-TR-1986 JUNE 1999

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5068

ARL-TR-1986 June 1999

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Ki C. Kim
Survivability/Lethality Analysis Directorate

Abstract

A computer program for calculating helicopter torque coefficients (C_Q) and thrust coefficients (C_T) as a function of a vehicle's forward speed has been developed in conjunction with the helicopter performance assessment project. The model is based on the energy principle, in which helicopter power is broken into three components: induced power, profile power, and parasite power. This report documents the basic mathematical model used in the code, along with the numerical solution scheme used in implementing the model. Results are calculated for the UH-60A Black Hawk helicopter for hover and different forward speed settings and correlated with existing flight test data. The effects of different disk loading on helicopter power requirements are also investigated. The present model agrees reasonably well with the flight test data, providing the author with a certain confidence in the helicopter aerodynamic model developed in the present study.

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ANALYTICAL CALCULATIONS OF HELICOPTER TORQUE COEFFICIENTS (C_Q) AND THRUST COEFFICIENTS (C_T) VALUES FOR THE **HEL**ICOPTER **PE**RFORMANCE (HELPE) MODEL

1. INTRODUCTION

As a Fiscal Year 1998 mission project, the Air System Engineering Analysis Team (ASEAT) of the Survivability/Lethality Analysis Directorate (SLAD) of the U.S. Army Research Laboratory (ARL) was tasked to develop an engineering analysis model to calculate the helicopter steady state performance. The model, which is to be used in support of helicopter ballistic vulnerability assessment projects, should be capable of determining the performance degradation of a helicopter when its engine is damaged during combat.

After literature surveys and lengthy discussions among team members as well as academia professionals (e.g., University of Maryland, Georgia Tech Research Institute, etc.) for a possible candidate program, ARL decided to adopt the existing **Hel**icopter **Pe**rformance (HELPE) code.**[1]** The reasons for the selection of the code are ease of use, quick turn-around time, and the availability of source code and a documentation report. HELPE requires many engineering data to be input, and most of them are fixed parameters specific to the helicopter to be investigated. For example, helicopter gross weight, empty weight, rotor diameter, rotor rpm, blade aerodynamic coefficients, available engine powers, etc., are required for the HELPE input.

Other necessary input data for the HELPE code is a set of helicopter torque coefficients (C_Q) and thrust coefficients (C_T) as a function of a vehicle's forward speed (μ). However, flight test data specifying these values are not readily available for most helicopters. To expand the applicability of the HELPE model, a computer code to numerically calculate these input values needed to be developed.

In this report, formulation and analysis details of the recently developed code for calculating C_Q and C_T of a generic helicopter system are presented, including brief descriptions of basic input-output relations of the code. Numerical results are obtained for UH-60 Black Hawk helicopter using the present code and correlated with flight test data.**[2]** Based on results obtained, conclusions are drawn, with some recommendations for future works.

2. NOMENCLATURE

c	Blade chord
c_0	Lift coefficient at zero angle of attack
c_1	Lift curve slope
C_d	Blade section drag coefficient
C_{d_0}	Blade mean drag coefficient
C_l	Blade section lift coefficient
$C_{m_{ac}}$	Blade section pitching moment coefficient about aerodynamic center
C_{D_f}	Fuselage drag coefficient
C_{l_f}	Fuselage rolling moment coefficient
C_{L_f}	Fuselage lift coefficient
C_{m_f}	Fuselage pitching moment coefficient
C_{n_f}	Fuselage yawing moment coefficient
C_P	Helicopter power coefficient
C_Q	Helicopter torque coefficient
C_T	Helicopter thrust coefficient
C_W	Helicopter weight coefficient
d_0	Viscous drag coefficient
d_1, d_2	Pressure drag coefficients
D_F	Fuselage drag
f_0, f_1	Pitching moment coefficients
$\overline{h}$	Vertical distance from helicopter center of gravity (CG) to hub center
M	Mach number
M_{inc}	Incidental Mach number normal to chord
N_b	Number of blades
R	Blade radius, *ft*
T	Rotor thrust, *lb*
V	Helicopter forward speed, *ft/sec*
x_{cg}, y_{cg}	Hub center position relative to helicopter CG in the X and Y directions, respectively
X_t	Distance between main rotor hub and tail rotor hub
Y_F	Fuselage side force
Y_{tr}	Tail rotor thrust
α	Blade section angle of attack, *radians (rad)*
α_{HP}	Hub plane tilt angle relative to flight direction
α_s	Longitudinal shaft tilt relative to wind axis, *rad*

β_0	Rotor coning angle, *rad*
$\beta_{1s}\beta_{1c}$	Lateral and longitudinal rotor disk tilt angle, respectively, *rad*
$\theta_{1c}\theta_{1s}$	Lateral and longitudinal cyclic trim input, respectively, *rad*
$\theta_{.75}$	Collective blade pitch at 75% radius, *rad*
θ_{FP}	Helicopter flight path angle relative to the longitudinal axis
θ_{tr}	Tail rotor collective control setting
μ	Advance ratio, $V/\Omega R$
σ	Rotor solidity ratio, $N_b c_m/\pi R$
ϕ_s	Lateral shaft tilt, *rad*
ρ	Air density, $slug/ft^3$
Ω	Rotor rotational speed, *rad/sec*

3. FORMULATION

3.1 Equivalency of C_Q and C_P

Let Q and P be the torque and power required for a helicopter to sustain the level forward flight, respectively. Then, based on the fundamental physics, we have the following relationship between P and Q:

$$P = Q\,\Omega \tag{1}$$

By expressing Q and P in terms of its coefficients and other helicopter parameters,

$$\begin{aligned} Q &= C_Q \rho A R (\Omega R)^2 \\ P &= C_P \rho A (\Omega R)^3 \end{aligned} \tag{2}$$

Substituting Equation (2) into Equation (1), we can obtain the following equivalency of C_Q and C_P:

$$C_Q = C_P \tag{3}$$

Therefore, we can calculate the power coefficients instead of the torque coefficients for the HELPE code input.

In the next section, formulations and procedure to calculate the helicopter power coefficient, C_P, are presented.

3.2 Helicopter Power Coefficient, C_P

From the well-known energy principle for rotary wing aircraft **[2]**, we can break the helicopter power into three fundamental components: induced power (P_i), profile power (P_o), and parasite power (P_p).

$$P = P_i + P_o + P_p \tag{4}$$

In terms of coefficients, helicopter power coefficient, C_P, can be expressed as follows:

$$C_P = C_{P_i} + C_{P_o} + C_{P_p} \tag{5}$$

in which C_{P_i}, C_{P_o}, and C_{P_p} are the coefficients of induced power (P_i), profile power (P_o), and parasite power (P_p), respectively.

3.2.1 *Induced Power, C_{P_i}*

Induced power is the power required to produce rotor thrust. Using the momentum theory **[3]**, the induced power coefficient can be simplified as follows (for details of derivation, see Reference 3):

$$C_{P_i} = \kappa \lambda_i C_T \tag{6}$$

in which λ_i is the induced velocity coefficient, C_T is the rotor thrust coefficient, and κ is an empirical factor to cover nonuniform flow and tip loss. Typically, a value of 1.15 is used for κ. Therefore, for given sets of rotor thrust (C_T) and forward speed (μ), the only parameter needed to calculate C_{P_i} is λ_i.

In general, the rotor-induced velocity, λ_i, can be calculated iteratively using the following two equations:

$$\lambda_i = \frac{C_T}{2\sqrt{\mu^2 + \lambda^2}} \qquad (7)$$
$$\lambda_i = \lambda - \mu \ \ \tan\alpha_s$$

in which λ is the in-flow ratio. In case of hover (i.e., $\mu = 0$), λ_i and λ become identical:

$$\lambda = \sqrt{\frac{C_T}{2}} \tag{8}$$

Therefore, the calculation of λ_i requires another parameter, the longitudinal tilt of the rotor shaft, α_S. This involves solutions of nonlinear systems of equations considering the vehicle equilibrium condition. The formulation and solution of the vehicle equilibrium equations are discussed in a later section.

3.2.2 *Profile Power, C_{P_o}*

Profile power is a power required to turn the rotor in air (i.e., viscous drag). Typically, the calculation of profile power requires a knowledge of the blade section profile drag coefficient, preferably including its dependence on angle of attack (α) and Mach number (M). Often, it is difficult to obtain a complete and reliable set of even static, two-dimensional airfoil data.

Alternatively, the rotor analysis can use a mean profile drag coefficient (C_{d_o}) to represent the overall effects of the blade drag on the rotor.**[4]** The use of a mean drag coefficient is sufficiently accurate for some purposes, such as preliminary design, or when detailed aerodynamic characteristics for the blade section are not available.

One of the major setbacks using the mean drag coefficient is that rotor analysis using the mean drag coefficient often fails to capture stall and compressibility effects in forward flight. Additional corrections or a more detailed analysis thus are required for rotors at extreme operating conditions.

In the present calculation, an improved approach to calculate a mean profile drag coefficient using a drag polar of the form **[5]** is adopted to calculate the profile power, along with the use of Prandtl-Glauert's compressibility correction.

In Reference 5, an estimation of C_{d_o} is given when the blade drag coefficient is known in the form of $C_d = \delta_o + \delta_1\alpha + \delta_2\alpha^2$:

$$C_{d_o} = \delta_o + \delta_1\overline{C}_L + \delta_2\overline{C}_L^{\,2} \tag{9}$$

in which $\overline{C}_L$ is the mean disk loading:

$$\overline{C}_L = \frac{6C_T}{\sigma} \tag{10}$$

Then, the coefficient of profile power is calculated as follows:

$$C_{P_o} = \frac{\sigma C_{d_o}}{8}\left(1+4.6\mu^2\right) \tag{11}$$

3.2.3 *Parasite Power, C_{P_p}*

Parasite power is a power required to overcome the drag of the helicopter. The estimation of helicopter parasite power is an important aspect of performance calculation because it establishes the propulsive force and power requirement at high speed. The power required to overcome the parasite drag of helicopter (D), can be expressed as

$$P_p = DV \tag{12}$$

in which V is the speed of helicopter.

By rewriting P_p in terms of its coefficients and other helicopter parameters, similar to Equation (2), we have

$$C_{P_p} = \frac{DV}{\rho A(\Omega R)^3} \tag{13}$$

Further, the drag force acting on a helicopter can be expressed as

$$D = \frac{1}{2}\rho V^2 f \tag{14}$$

in which f is the parasite drag area of helicopter including rotor hub. Except for compressibility or Reynolds number effects, f is generally independent of speed.

By substituting Equation (14) into Equation (13), we obtain the following equation for the parasite power coefficient:

$$C_{P_p} = \frac{1}{2}\;\frac{V^3}{(\Omega R)^3}\;\frac{f}{A} = \frac{1}{2}\frac{f}{A}\mu^3 \tag{15}$$

in which f/A is the equivalent flat plate area correlated with rotor area (A). It is found that f/A can be as high as 0.025 for old helicopters, about 0.01 to 0.015 for helicopters in current production, and 0.004 to 0.008 for a clean helicopter design.

In this section, it was shown that power coefficient, C_P, can be calculated from Equations (6), (11), and (15). However, as mentioned earlier, the solution of Equation (6) requires a

knowledge of rotor shaft tilt angle, α_s, for a given set of thrust coefficient and forward speed, and thus a vehicle trim solution. In the next section, a formulation and solution procedure for vehicle trim is presented.

3.3 Vehicle Trim Solution

Propulsive trim, which simulates an aircraft free flight condition, is used to calculate the initial rotor control settings as well as the vehicle orientation (i.e., α_s and ϕ_s). The solution is determined from the overall equilibrium equations: three force (vertical Z, longitudinal X, and lateral Y) and three moment (pitch, roll, and yaw) equations. These are

$$\begin{aligned}
F_1 &= F^H_{X_o} + D_F cos\alpha_{HP} - T sin\alpha_s = 0 \\
F_2 &= F^H_{Y_o} + Y_F cos\phi_s - Y_{tr} + T sin\phi_s = 0 \\
F_3 &= F^H_{Z_o} - T cos\alpha_s cos\phi_s - D_F cos\phi_s sin\alpha_{HP} + Y_F sin\phi_s = 0 \\
F_4 &= M^H_{X_o} + M_{x_F} + T\left(\bar{h} cos\alpha_s sin\phi_s - y_{cg} cos\phi_s\right) + Y_F\left(\bar{h} cos\alpha_s cos\phi_s + y_{cg} sin\phi_s\right) = 0 \\
F_5 &= M^H_{Y_o} + M_{y_F} + T\left(\bar{h} sin\alpha_s - x_{cg} cos\alpha_s\right) + D_F\left(-\bar{h} cos\alpha_{HP} + x_{cg} sin\alpha_{HP}\right) = 0 \\
F_6 &= M^H_{Z_o} + M_{z_F} - X_t Y_{tr} = 0
\end{aligned} \tag{16}$$

in which F_1, F_2, and F_3 are, respectively, the force equilibrium equations in the X, Y, and Z directions, and F_4, F_5, and F_6 are the rolling, pitching, and yawing moment equilibrium equations, respectively. Also, D_F is the fuselage drag; Y_F is the fuselage side force; Y_{tr} is the tail rotor thrust; T is the main rotor thrust; x_{cg} and y_{cg} and $\bar{h}$ are, respectively, the relative location of the rotor hub center with respect to the vehicle CG in the X, Y, and Z directions; X_t is the nondimensional length (divided by rotor radius) between the main rotor hub and the tail rotor hub; and α_s and ϕ_s are the longitudinal and lateral shaft tilts, respectively. Furthermore,

$$\alpha_s = \alpha_{HP} - \theta_{FP} \tag{17}$$

in which α_{HP} is the hub plane tilt relative to the flight direction, and θ_{FP} is the flight path angle relative to the longitudinal axis.

For a specified thrust coefficient C_T and a forward speed (μ), the unknown quantities to be determined from the vehicle equilibrium equations are

$$\mathbf{u}^T = \lfloor \alpha_s, \phi_s, \theta_{.75}, \theta_{1c}, \theta_{1s}, Y_{tr} \rfloor. \tag{18}$$

These values are recalculated iteratively using Newton's method.

$$\mathbf{u}_{i+1} = \mathbf{u}_i + \Delta\mathbf{u}_i \tag{19}$$

More details about trim analysis and results of several case studies are available in Reference 6.

4. RESULTS AND DISCUSSION

Numerical results are calculated for the UH-60A Black Hawk helicopter for level flight conditions. Some of important physical and aerodynamic characteristics of this helicopter rotor are given in Table 1.

Table 1. UH-60A Black Hawk Helicopter Characteristics

Aircraft gross weight	16,260 lb
Number of blades, N_b	4
Radius, R	26.83 ft
Blade chord, c	1.75 ft
Solidity, σ	0.083
Lock number, γ	8.
Blade airfoils	SC1095, SC1095-R8 (tip)
Rotational speed, Ω	27 rad/sec
Flap frequency, ν_β	1.05/rev
Nominal lift curve slope, a	5.73/rad

Calculated power coefficients for UH-60A during different rotor thrust conditions are correlated with flight data as shown in Figures 1 through 8.

Figure 1 shows the correlation of helicopter power coefficients with flight test data for a thrust coefficient (C_T) of 0.0066. The variation with speed of the total power coefficient ($C_P = C_{P_i} + C_{P_o} + C_{P_p}$) and its three individual components (i.e., C_{P_i}, C_{P_o}, and C_{P_p}) are plotted along with the flight data. From this plot, it is observed that the induced power is the largest component in hover, but it decreases with speed. The profile power exhibits a slight increase with speed. The parasite power is negligible at low speeds but increases proportionally to μ^3 to dominate at the high speed region. Therefore, the total power coefficient is high at hover ($\mu = 0$), has a minimum value in the low speed region, and then increases again at high speed because of

the parasite power. This trend is quite agreeable with References 2 through 4. The results obtained from the present analysis agree very well with flight test, as shown in Figure 1.

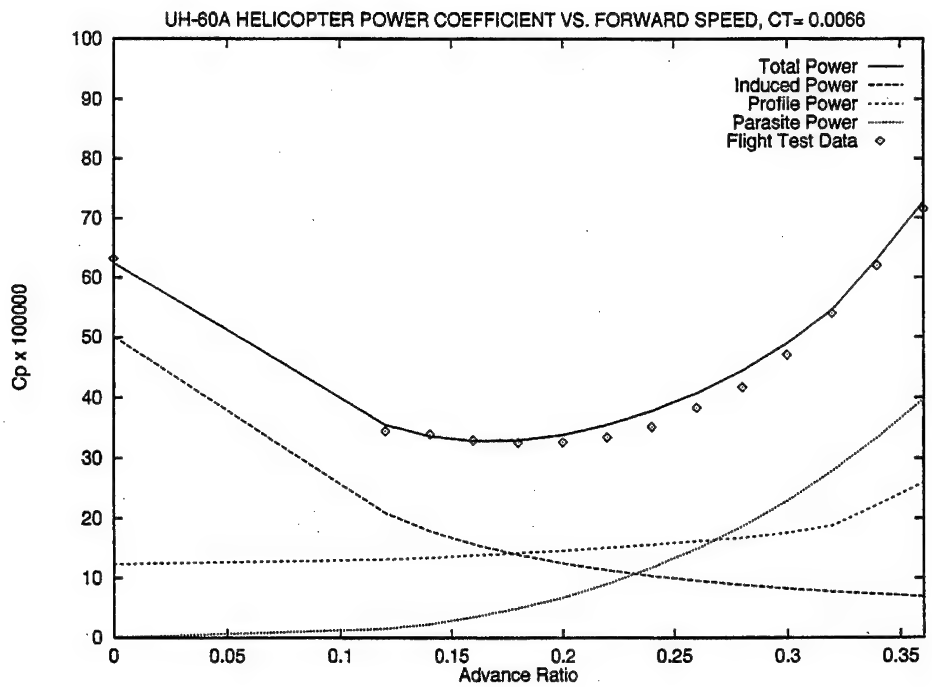

Figure 1. <u>Variations of Helicopter Power Coefficient (C_P) Versus Forward Speed (C_T = 0.0066)</u>.

Figures 2 and 6 show the similar correlations but with different rotor thrust settings. Figure 7 shows the correlation of power coefficient at very high thrust condition (C_T = 0.0102). In low speed regions, the analytical results correlate well with flight data. However, the present model under-predicts the power coefficients at the high speed region (high speed/high thrust). This is most likely because of the shock-boundary layer interactions, which are not accurately modeled in the present study. In the future, the use of full Navier-Stokes computational fluid dynamics (CFD) code, along with the wind tunnel experiment, may improve predictions of rotor and fuselage drag.

The effects of disk loading on the helicopter power required are shown in Figure 8. As expected, the power required increases as the rotor thrust increases. This is mainly attributable to high in-flow velocity associated with high disk loading at low speeds and because of compressibility/stall effects at high speed.

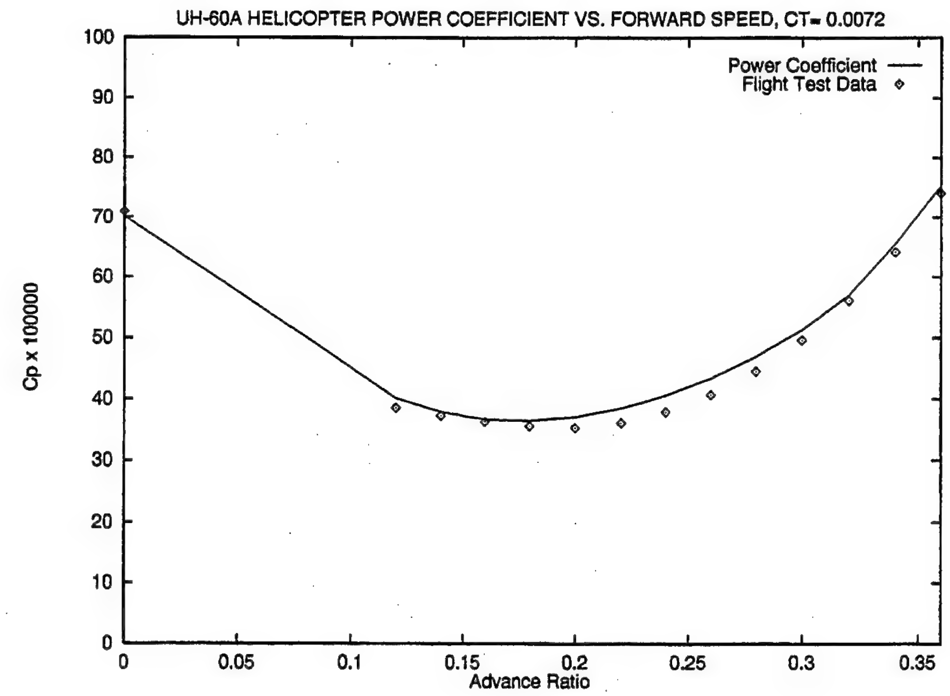

Figure 2. <u>Variations of Helicopter Power Coefficient (C_P) Versus Forward Speed ($C_T = 0.0072$)</u>.

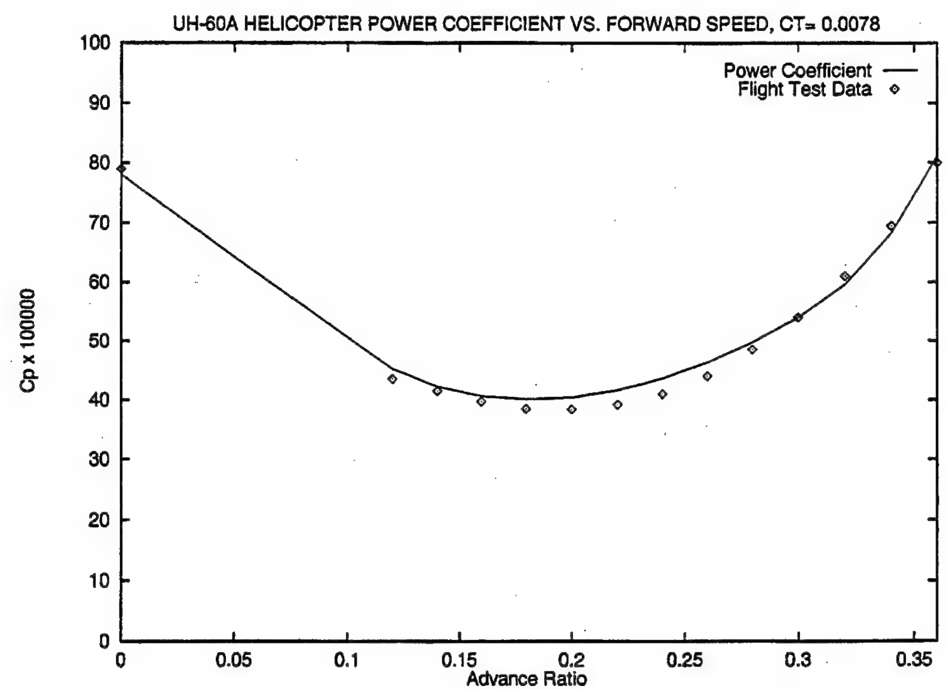

Figure 3. <u>Variations of Helicopter Power Coefficient (C_P) Versus Forward Speed ($C_T = 0.0078$)</u>.

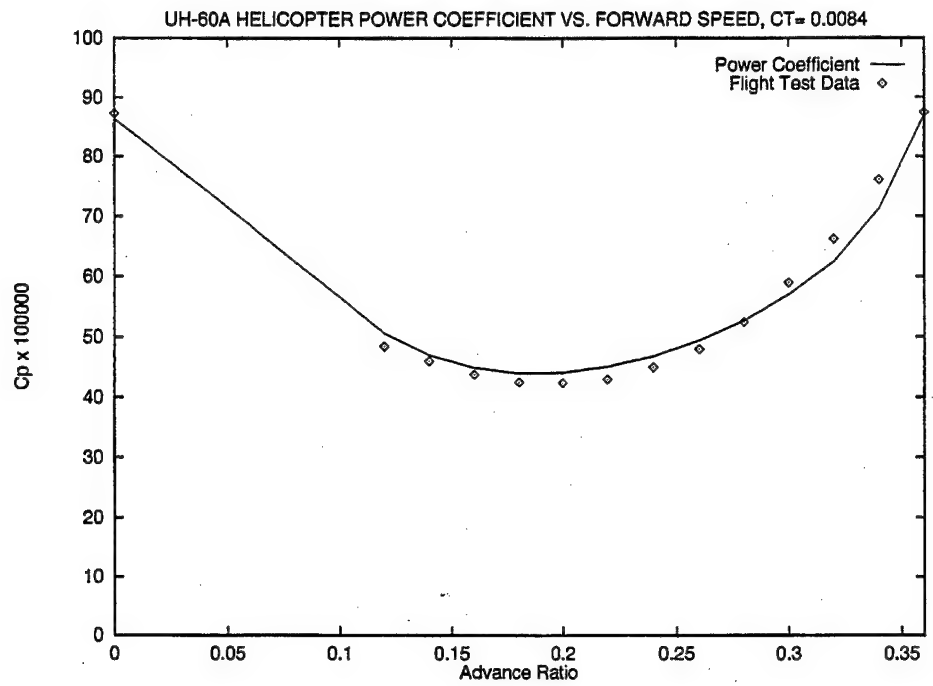

Figure 4. Variations of Helicopter Power Coefficient (C_P) Versus Forward Speed ($C_T = 0.0084$).

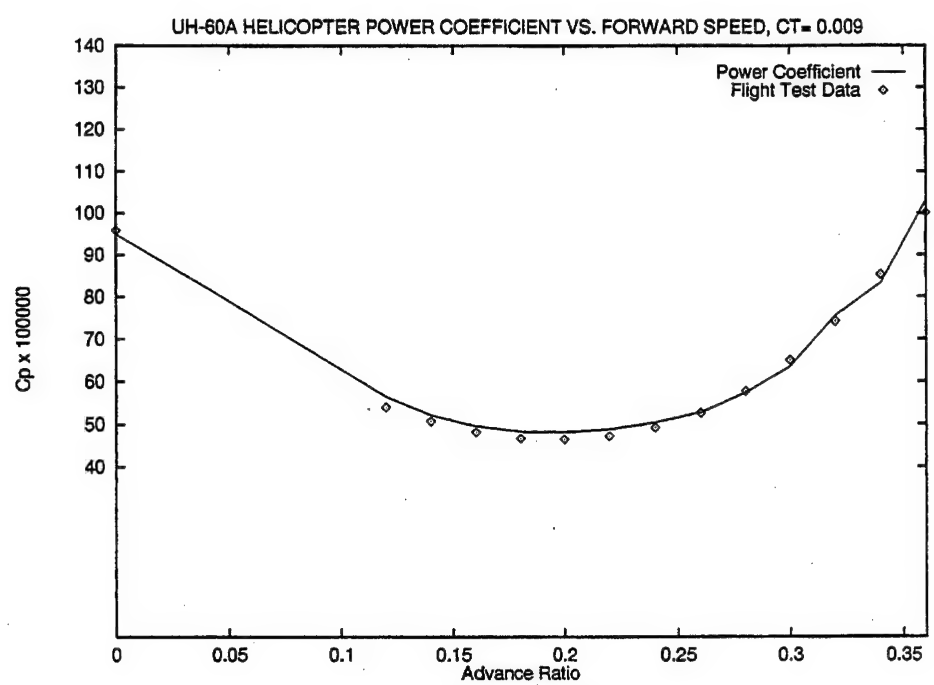

Figure 5. Variations of Helicopter Power Coefficient (C_P) Versus Forward Speed ($C_T = 0.0090$).

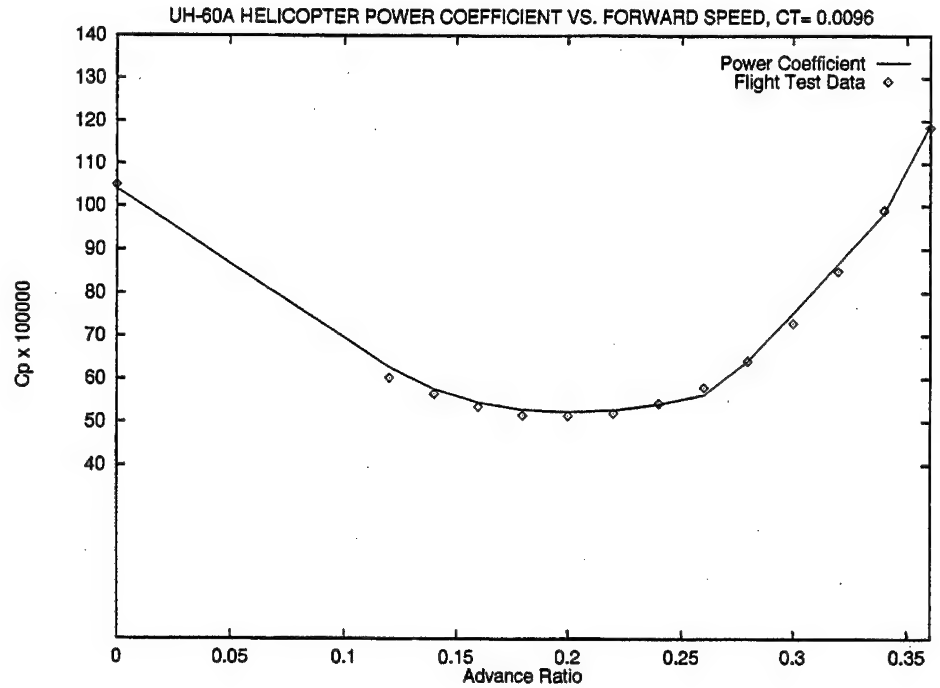

Figure 6. Variations of Helicopter Power Coefficient (C_P) Versus Forward Speed ($C_T = 0.0096$).

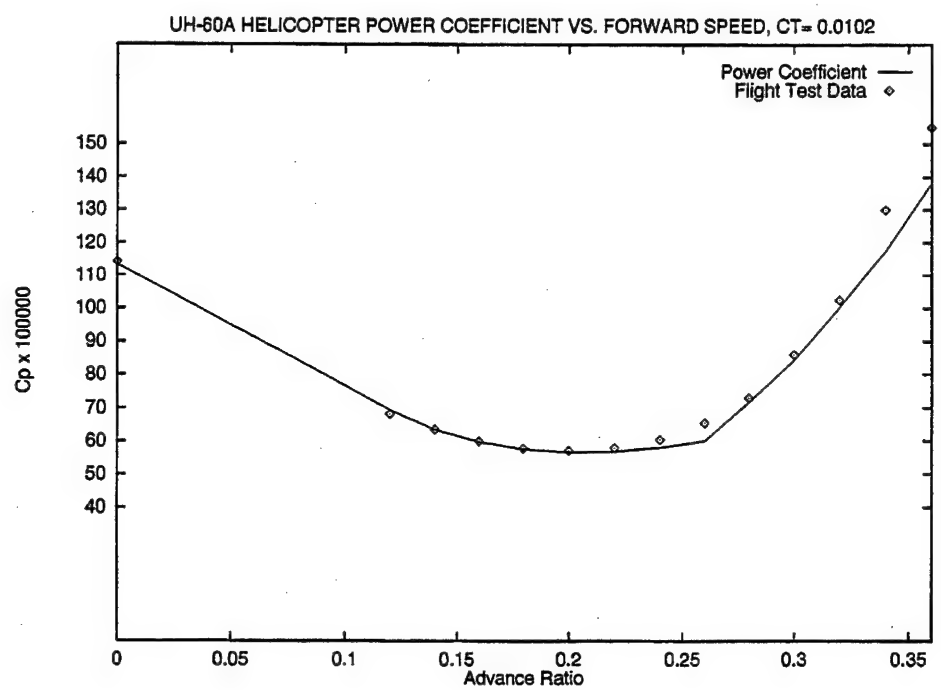

Figure 7. Variations of Helicopter Power Coefficient (C_P) Versus Forward Speed ($C_T = 0.0102$).

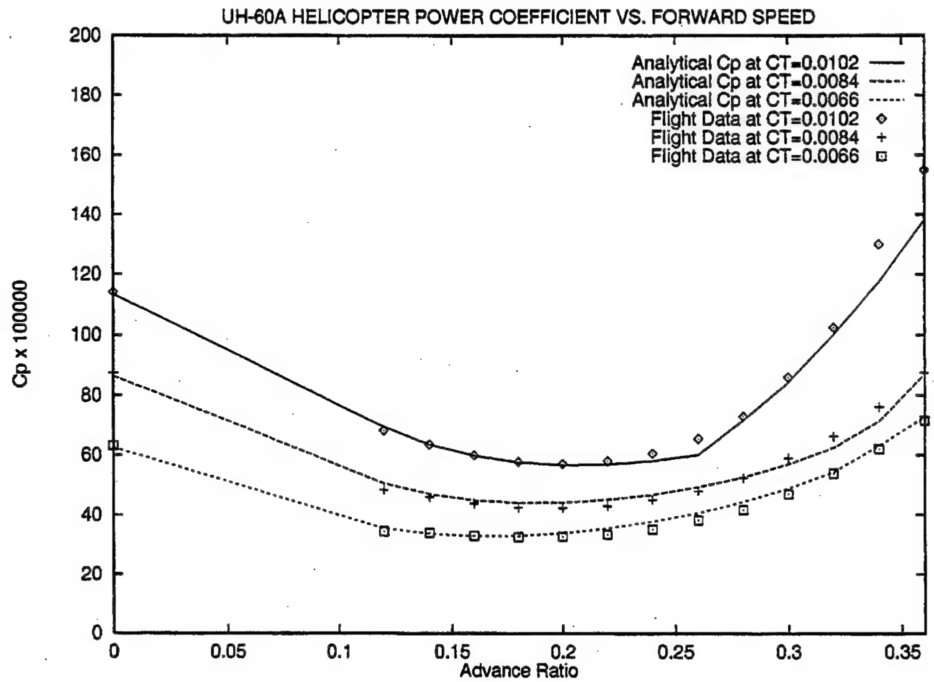

Figure 8. The Effects of Disk Loading on Helicopter Power Coefficient (C_P).

Overall, numerical results obtained from the present analysis agree reasonably well with available flight test data.**[1]**

Presently, another activity is under way to further validate the present model with a different helicopter, an AH-64D Longbow Apache attack helicopter. Initial results from the AH-64D study also show good correlation with flight data, providing the author with a certain confidence in the helicopter aerodynamic model developed in the present study.

5. SUMMARY

A computer program calculating helicopter power coefficients and thrust coefficients as a function of a vehicle's forward speed is developed in support of the helicopter performance assessment project. The model is based on the energy principle, in which helicopter power is broken into three components: induced power, profile power, and parasite power. For induced power calculation, rotor shaft tilt angle obtained from the vehicle trim solution is used. Numerical results are calculated for the UH-60A Black Hawk helicopter for hover and different forward speed settings and correlated reasonably with existing flight test data.

Based on results obtained in this study and further correlation study, the present computer model can be used to estimate sufficiently accurate power coefficients for a generic helicopter.

5.1 Recommendation for Future Study

In the present study, an attempt was made to include stall and compressibility effects in the helicopter power calculation by using the polar form of blade drag coefficient along with Prandtl-Glauert's compressibility correction. Based on results obtained, however, additional corrections or a more detailed analysis is required for rotors at extreme operating conditions (i.e., high speed/high disk loading). A future study investigating these phenomena would be of great interest.

The computer code can be used to generate the trim parameters, $\alpha_s, \theta_{.75}, \theta_{1c}, \theta_{1s}$, required as level flight conditions for other ARL vulnerability analyses.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
June 1999

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
Analytical Calculations of Helicopter Torque Coefficient (C_Q) and Thrust Coefficient (C_T) Values for the Helicopter Performance (HELPE) Model

5. FUNDING NUMBERS
Project No. 1L162618AH80

6. AUTHOR(S)
Kim, K.C. (ARL)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Survivability/Lethality Analysis Directorate
Aberdeen Proving Ground, MD 21010-5068

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Survivability/Lethality Analysis Directorate
Aberdeen Proving Ground, MD 21010-5068

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARL-TR-1986

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

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14. SUBJECT TERMS
helicopter performance
trim stall
rotor aerodynamics

15. NUMBER OF PAGES
30

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102